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Behaviour of engineered cementitious composites and hybrid engineered cementitious composites at high temperatures

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HIGHLIGHTS

- Behaviour of ECC and hybrid ECC subjected to compression load at high temperatures.
- Behaviour of ECC and hybrid ECC subjected to flexural load at high temperatures.
- Improve the integrity of ECC subjected to compression and flexural load at high temperatures using steel fibres.
- Using a finite element model to investigate the experimental results. .

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ABSTRACT

The behaviour of engineered cementitious composites (ECC) specimens using polyvinyl alcohol (PVA) fibres and hybrid engineered cementitious composites (HECC) using PVA fibres and steel fibres (two different types) was experimentally investigated. The experiments included compression and flexural tests at different temperatures ranging from 20 °C to 600 °C. Under uniaxial compression load the HECCs specimens produced less debris (from 200 °C to 600 °C) compared to ECC counterparts. The flexural tests results revealed that the load bearing capacity and deflection of HECCs specimens were less vulnerable up to 100 °C compared to ECC specimens. Under higher temperatures the ECC specimens' behaviour was brittle, while HECCs specimens exhibited a deflection-softening behaviour. Then a finite element model was employed to investigate the flexural tests results obtained from experiments.

1. Introduction

Engineered Cementitious Composites (ECC) include a range of ductile fibre reinforced mortars that exhibit a strain-hardening behaviour under uniaxial tension, typically with a strain capacity up to 5% [1]. This strain-hardening behaviour results from the capability of the material to develop a large number of uniform and fine cracks, characterised by the average widths of less than 100 μm [1–3]. Typically, a polymeric fibre such as polyethylene (PE) or polyvinyl alcohol fibres (PVA) are employed to bridge the loads throughout the fine cracks [1]. The hybrid fibre ECC (HECC) using a combination of steel fibres (high-modulus fibres) and polymeric fibres (low modulus fibres) was primarily developed to achieve a desired balance between the ultimate tensile strength and the strain capacity of the material required for impact- and blast-resistant structures [4]. During the past decades, various types of ECCs have been developed including self-compacting ECC [5], sprayable ECC [6], high-early strength ECC [7,8], lightweight ECC [9], green ECC [10,11], and self-healing ECC [12]. These materials can be used for a wide range of applications such as dissipation of energy (seismic-, impact- and blast-resistance structures), using as the free-crack surface layer (dams and irrigation canals), high fatigue resistance and durable material (bridges, roads, railways and retrofitting purpose) [13–15]. Despite the widespread applications of ECC, studies about its behaviour under elevated or high temperatures (i.e. solar emission, fire, gas explosion and blast) are limited.

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It is established that the tensile behaviour of ECC is sensitive to the change of temperature [16,17]. When subjected to high temperature, the ECC material exhibited a reduction in the characteristic tensile strength accomplished by decreasing (or vanishing) the strain hardening capacity [18]. Another study has shown that the polymeric fibres of ECC (i.e. PVA fibre) can decrease the degree of spalling and explosion spalling at high temperatures [19]. This is achieved by providing a series of pores to release the pressure of evaporated water that is trapped inside the ECC matrix. As a result a more consistent performance at high temperature is exhibited by ECC [19,20]. It is observed that up to 400 °C the compressive strength of ECC is stable and close to ambient temperature [20]. However, beyond 400 °C the compressive strength of ECC considerably decreases (about 40%) compared to ambient temperature. The strain-hardening performance of ECC is also vulnerable at high temperatures. The reduction of ECC tensile strength and ductility at high temperature can lead to a brittle failure [18]. Studying the tensile behaviour of ECC under elevated temperature reveals that as temperature increases up to 100 °C, the strain capacity increases due to the reduction of bond strength between the polymeric fibres and matrix under elevated temperature. The fibres can develop a longer free length and higher elastic and plastic deformation results in wider cracks in the ECC. However at 150 °C, it was found that the ECC ability to form multiple cracks disappeared as a result of the deterioration of the fibre's mechanical properties [18]. The studies on the behaviour of steel fibre reinforced mortars revealed that using the steel fibre can increase the compressive strength, Young's modulus and ultimate flexural strength while decreasing the ultimate strain capacity at high temperature [21]. It is observed that the steel fibre reinforced concrete exposed to high temperatures exhibited less spalling, and more energy absorption during the bending test followed by ductile mode of failure compared to concrete specimens. The steel fibre also increased the integrity of samples compared to concrete counterparts [22]. The benefits stemming from the use of steel fibres can potentially improve the ductile performance of ECC exposed to high temperatures. However, the HECC performance under high temperatures has not yet been studied and needs to be evaluated aiming to enhance the ECC performance exposure to high temperatures.

This paper investigates the performance of ECC and HECCs at high temperatures. The mechanical properties of ECC (using PVA fibres), H6ECC (using PVA and 6 mm steel fibres) and H13ECC (using PVA and 13 mm steel fibres) were studied under temperatures ranging from 20 °C to 600 °C (as these temperatures were the thresholds of the employed furnace). The experiments involved tensile, compression and flexural tests. The test variations were a volume fraction of steel fibres (0% and 0.75%), the length of steel fibres (6 mm and 13 mm) and temperature ranging from 20 °C to 600 °C. The schedule of tests for different temperatures is presented in Table 1.

2. Material

The ECC and HECCs mixture used in the experiments comprised of cement type I 52.5 N, fine silica sand of average particle size 120 μm and SV80 fly-ash. Specimens' mixtures proportions are demonstrated in Table 2. For hybrid ECCs 1.75% of PVA fibre by volume were added to mixtures and 0.75% of 6 mm (St 6) and 13 mm (St 13) steel fibre by volume were added to the H6ECC and H13ECC mixture respectively. The mechanical properties of Polyvinyl Alcohol (PVA), and steel fibres (straight steel fibres) used in the experiment are presented in Table 3.

For tensile tests, the fresh ECC and HECCs were cast in moulds and covered with plastic film (to avoid water evaporation) for 24 h. Then specimens were demoulded and immersed in water in a curing tank at 20 ± 3 °C for 28 days until the testing date. For the compression and bending tests; however, after demoulding, the specimens were immersed in water for 21 days and then cured for 7 days in the laboratory environment out of water (20 ± 3 °C and 60% humidity) to reduce the possibility of spalling at high temperature.

3. Tests method

3.1. Tensile test

A series of uniaxial tensile tests were conducted on the dog-bone specimens according to Japanese recommendations [23]. The dog-bone specimens' dimensions are presented in Fig. 1a. The load was applied in displacement increments at a rate of 1 mm/min using a 100 kN Instron testing machine and two LVDTs positioned on both sides of the sample measured the relative displacement on the 80 mm central span (see Fig. 1b).

3.2. Compression test

The compression tests were carried out in accordance to BS 1881-116 [24]. The compression specimens' dimensions were 50 mm × 50 mm × 50 mm cubes (see Fig. 2c). A 600 kN Instron testing machine with integrated heating chamber was used for establishing the compressive strength of the cube samples (see Fig. 2a). The displacement increments at a rate of 1 mm/min were used for all tests. The samples were subjected to 6% compression strain. During the test, vertical displacement of the crosshead was measured by Instron machine. Furthermore, a digital camera (DC) was employed to capture the specimen's behaviour during the tests. In order to digitise the photographic evidence, appropriate contrast was applied on the surface of specimens (see Fig. 2c).

3.3. Bending test

A 600 kN Instron testing machine with integrated heating chamber applied load in displacement increments at a rate of 1 mm/min on the prisms. The prisms' dimensions were 170 mm × 40 mm × 20 mm (see Fig. 2d). The load applied was measured using a crosshead of the Instron machine. Each specimen was tested as a simply supported beam with a clear span of 150 mm, the span between the two point loads was 40 mm and the span between each points load and support was 55 mm (Fig. 2d). The vertical deflection was measured by the Instron machine and also a digital camera was used to capture the performance of specimens during the tests.

3.4. Heating regime

In an attempt to establish the effect of temperature on the behaviour of ECC and HECCs, a series of samples were initially put in a furnace in which the temperature was increased at a rate of 10 °C per minute until the target temperature was attained (Fig. 2b). The temperature then remained constant for 30 min then tests were carried out under target temperatures inside the heating chamber.

Table 1
Schedule of experiments.

Test	Temperatures (°C)						
	20	60	100	150	200	400	600
Tensile	✓	NA	NA	NA	NA	NA	NA
Compression	✓	NA	NA	NA	✓	✓	✓
Flexural	✓	✓	✓	✓	✓	✓	✓

✓: Test is carried out.
NA: Test is not carried out.